

AIR-GAP DETECTION IN DIELECTRIC MATERIALS BY A STEP-FREQUENCY MICROWAVE TECHNIQUE

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INTRODUCTION

Most microwave NDE has been performed using continuous wave excitation and reception, due to the general availability of such equipment and the acceptable procedure of extracting information from the amplitude and phase of such signals. With the availability of sources that can be swept over a band of frequencies, the amplitude and phase information can be converted via the Fourier Transformation to the impulse response in the time domain. Instead of searching for changes in the amplitude and phase of microwave reflected from boundaries, interfaces, and defects, this time domain approach concentrates on the recognition of "echoes". This approach is implicit in some of the more complex approaches in microwave imaging [1-3]. It is the purpose of this paper to demonstrate that this approach facilitates the detection of internal defects using microwave, in a manner similar to the practice of pulse-echo ultrasound. The time delay for a microwave "echo" is related to the location, and the Fourier transformed amplitude is related to some characteristics of the defect inside the material.

IMPULSE RESPONSE

The complex reflection coefficient of a monochromatic plane wave from a dielectric slab in free space, of thickness d and complex permittivity ϵ ($\epsilon = \epsilon_r \epsilon_0 (1 + j \tan \delta)$), is

$$R = r(1 - e^{-2jkd}) / (1 - r^2 e^{-2jkd}) \quad (1)$$

where ϵ_r is the relative permittivity of the material, ϵ_0 is the permittivity in free space, $\tan \delta$ is the material loss tangent,

r is the polarization dependent, Fresnel reflection coefficient of a plane wave incident on a dielectric boundary, k is the length of the wave vector inside the dielectric [4]. The expressions when the dielectric slab is backed by a perfect conductor can be found in Ref. 5.

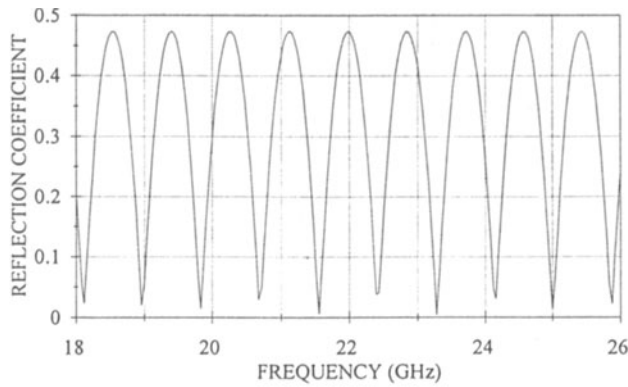
These reflection coefficients in real frequencies can be Fourier transformed to give the impulse response, the magnitude of which represents in the time domain the pulse reflection characteristics of the dielectric slab. This impulse response was identified previously by Gammell as the analytic signal in the context of ultrasound [6, 7]. The current approach in obtaining the microwave pulse reflection characteristics follows his ultrasonic approach. Before carrying out the Fourier transformation, windowing as well as phase shifts can be incorporated into the continuous wave reflection coefficients, in order to modify the amplitude of side lobes and to introduce time delays in the pulse-echo train.

PLANE WAVE PREDICTIONS

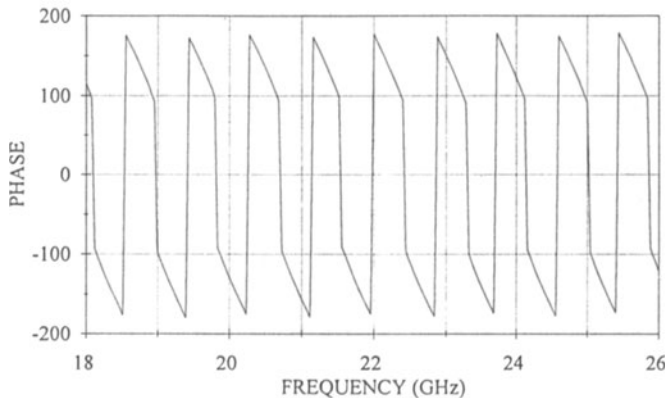
In Fig. 1 are shown the calculated amplitude and phase of the reflection coefficients for a dielectric slab of 10.39 cm in thickness, relative permittivity of 2.8 and a loss tangent of zero, for plane waves polarized perpendicular to the plane of incidence at normal incidence. The interference of the multiply reflected waves gives rise to the oscillatory pattern as the frequency was varied from 18 to 26 GHz. The corresponding magnitude of the impulse response, obtained via Fourier transformation, is shown in Fig. 2. This is a direct analogue of a pulse-echo train generated in pulsed ultrasound. The relative amplitude of the second pulse, corresponding to the back wall echo (traveled one round trip through the slab) and that of the third pulse, corresponding to waves traveled two round trips through the slab, are 0.93 and 0.06 respectively, when the amplitude of the first echo, corresponding to the front surface reflection, is taken to be unity. The separation of these echoes in time are determined by the relative permittivity. A pulse echo train for microwave reflection from an air gap of 0.02 cm in thickness, existing between two pieces of 6.00 cm thick material with a relative permittivity of 2.6 is shown in Fig. 3. It is evident that air-gaps can be detected by examining such transformed echo patterns in the time domain.

EXPERIMENTAL APPROACH

An experimental system for collecting microwave reflection data from a dielectric slab is shown in Fig. 4. In order to approximate the conditions of plane wave propagation without the need for excessively long separations between the antennas, a focussing lens was used. This also increased the power density at the material to enhance defect detection. All the data to be



(a)



(b)

Figure 1. (a) The amplitude, (b) the phase of the reflection coefficient vs. frequency for perpendicularly polarized plane waves at normal incidence to a dielectric slab of 10.39 cm in thickness, with a relative permittivity of 2.8 and lossless.

presented here were collected with the material front surface separated from the lens by twice its focal length. The reflection coefficients over a frequency band were measured with a network analyzer, which was equipped with analyzing software to calculate and display the Fourier transformed time domain pulse-echo train subsequent to data collection.

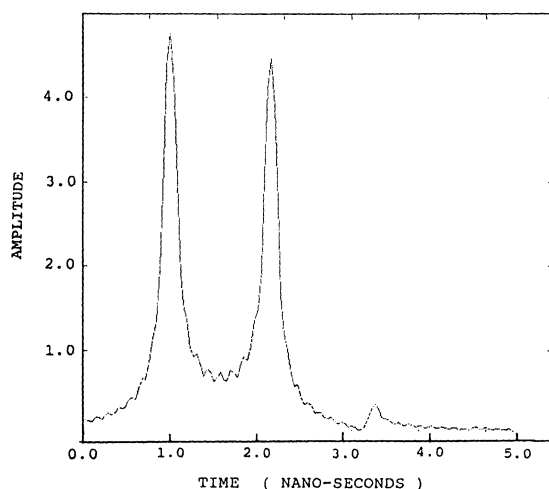


Figure 2. The magnitude of the impulse response calculated from the amplitude and phase information in Figure 1 for the dielectric slab.

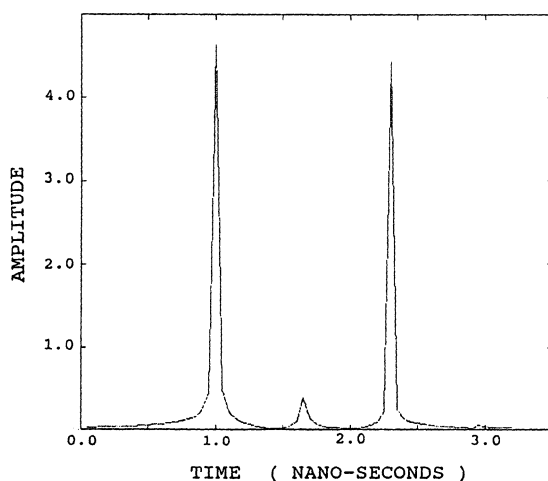


Figure 3. The magnitude of the impulse response calculated for a dielectric slab of 12.00 cm in thickness, a relative permittivity of 2.6 and lossless. An air-gap of 0.02 cm in thickness existed midway between the front and the back surface of the slab.

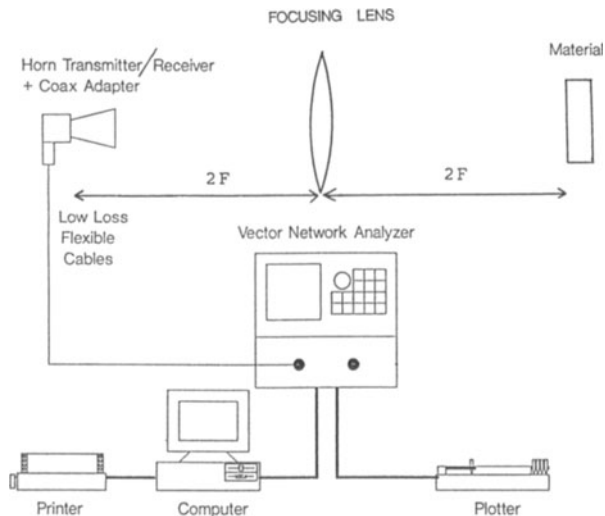


Figure 4. Experimental set-up of the measurement system. $2F$ was 26.0 cm.

EXPERIMENTAL RESULTS

Figure 5 shows the magnitude of the impulse response for reflection of microwave from a lucite slab in free space. The thickness and permittivity were the same as those used in the calculations for Fig. 1 and 2. It is seen that the time separating the front surface and the back surface reflections agreed quite well with that predicted by the plane wave model. However, the amplitude of the back wall reflection appeared to be less than predicted. This was probably due to the imperfection of the calibration procedure which attempted to compensate for the impedance mismatch and losses associated with cables, connectors and fixtures used in the measurement setup, as well as the limitations in approximating plane wave conditions at the focal spot of the lens.

In Figure 6 are shown the impulse responses of three-layer systems consisting of an air-gap of 0.005, 0.018, and 0.038 cm in thickness, sandwiched between two layers of lucite with thickness of 4.99 and 5.40 cm. The air-gap signal, peaking between the front surface and the back wall reflections, increased as the thickness of the gap increased.

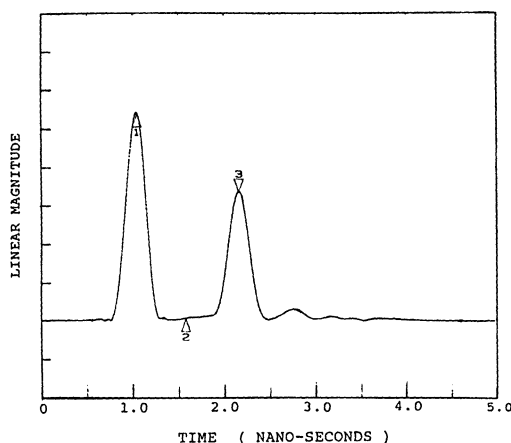


Figure 5. The magnitude of the impulse response converted from the complex reflection coefficients over the frequencies of 18-26 GHz, measured on a dielectric slab 10.39 cm in thickness, a relative permittivity of 2.8 and a loss tangent less than 0.05.

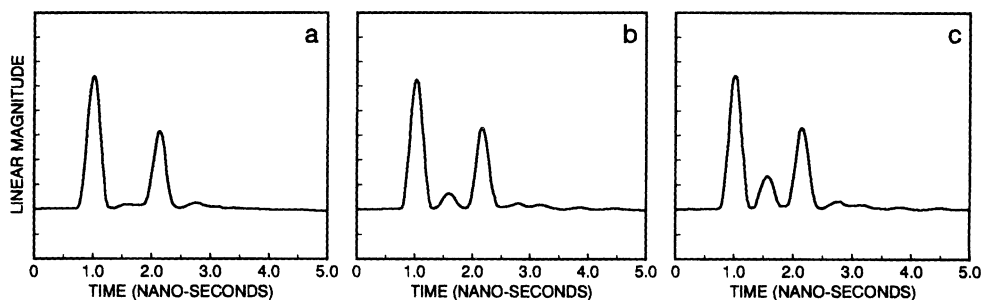


Figure 6. The magnitude of the impulse response converted from the complex reflection coefficients measured over the frequencies of 18-26 GHz on a dielectric with an internal air-gap. The thickness of the air-gap was: (a) 0.005 cm, (b) 0.018 cm, and (c) 0.038 cm.

In Figure 7(a) is shown the response associated with the intermediate layer when the air-gap of 0.018 cm in thickness was replaced by polyethylene. A centrally located void of either 0.032 or 0.064 cm in diameter was introduced in this layer. As this diameter increased, the peak height increased as shown in Fig. 7(b) and 7(c). When these voids were filled with distilled water, the signal level increased, as shown in Fig. 7(d) and 7(e).

CONCLUSIONS

By Fourier transformation, continuous microwave signals reflected from a dielectric slab can be represented as pulse-echo trains in the time domain. We have shown that the amplitude of the echoes associated with material boundaries and voids was related to their geometric and physical characteristics. As expected, the contrast of these voids increased when they were filled with water as a result of its high dielectric constant. Instead of searching for small changes in the amplitude and phase of multiply reflected signals, this time domain approach for defect detection may be advantageous for microwave NDE.

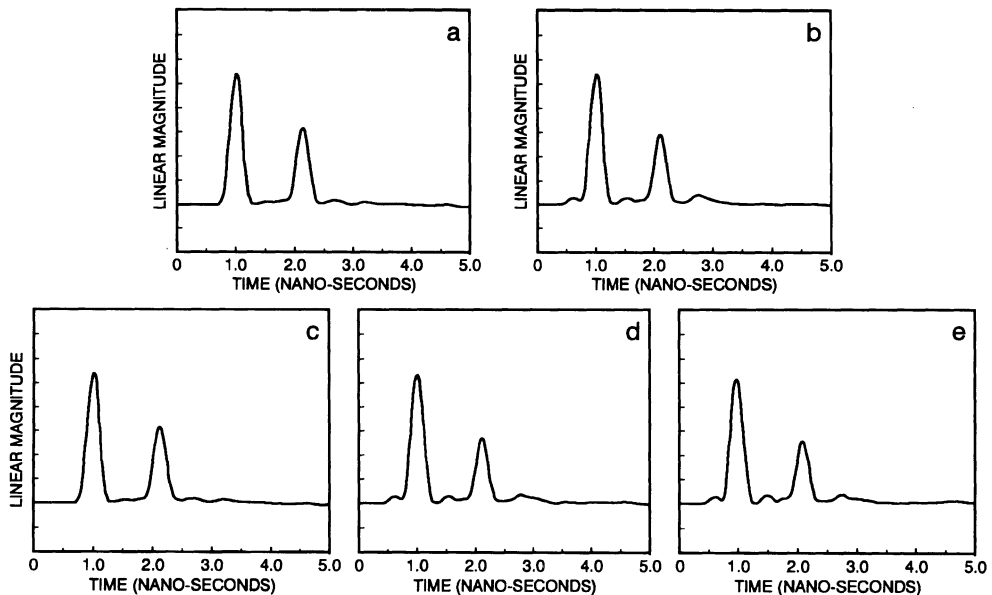


Figure 7. The magnitude of the impulse response for material filled voids. (a) an internal polyethylene layer of 0.018 cm in thickness existed, (b) a central void of 0.32 cm in diameter in the polyethylene, (c) void diameter of 0.64 cm, (d) water filled 0.32 cm void, (e) water filled 0.64 cm void.

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